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# MAMMOTH Flow: Making a Mixing Measurement of Two-phase Flow

Joseph Brown Tipton

*University of Tennessee - Knoxville*

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## UNIVERSITY HONORS PROGRAM

### SENIOR PROJECT - APPROVAL

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PROJECT TITLE: MAMMOTH Flow: Making A Mixing Measurement Of Two-phase Flow

I have reviewed this completed senior honors thesis with this student and certify that it is a project commensurate with honors level undergraduate research in this field.

Signed: Dr. Masood Parang, Faculty Mentor

Date: August 5, 2002

Comments (Optional):



## **M.A.M.M.O.T.H Flow: Phase II**

### **"Making A Mixing Measurement Of Two-pHase Flow"**

*Topic Area: Heat Transfer / Fluid Dynamics*



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## ABSTRACT

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The NASA Reduced Gravity Student Flight Opportunity Program (RGSFOP) allows undergraduate students to conduct meaningful microgravity research aboard NASA's KC-135 "Weightless Wonder". The KC-135 flies a parabolic flight trajectory to simulate up to thirty seconds of weightlessness or microgravity. This marks the second year a team from the University of Tennessee has participated in this prestigious program.

The movement of two-phase flows is an area of interest in microgravity conditions where evaporation and fluid transfer occur. One key application involves heat transfer from solids to liquids in the presence of vapor barriers. In order to gain a better understanding of these situations, the various issues of two-phase tube flow under microgravity conditions need to be studied.

As a detailed follow-up to last year's MAMMOTH Flow experiment, the first objective of this experiment is to simulate film boiling by injecting air into a pipe with liquid flow. As the apparent gravity level is reduced, the mechanics of the flow are expected to change resulting in the creation of a circumferential air barrier between the fluid and pipe wall.

Once this is accomplished, the second objective is to ascertain the usefulness of geometrical pipe changes in mixing the separated two-phase flow in an effort to augment heat transfer in microgravity conditions. Two devices will be tested that utilize helical ribbon and variable diameter inserts. It is believed that the helical ribbon will create a desirable phase distribution for heat transfer applications under microgravity conditions by removing the simulated vapor barrier from the pipe wall/heating surface. Similarly, the variable diameter insert will create flow turbulence resulting in desirable mixing of the

two-phases and fluid contact with the heating surface. These devices will be compared both qualitatively and quantitatively to a smooth pipe configuration to determine their usefulness in promoting heat transfer in two-phase flow microgravity conditions.

## STATEMENT OF AUTHORSHIP

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Credit should be given to the individuals on the MAMMOTH Flow team who assisted in the preparation of the documentation required by NASA for this project. Engineering graduates Randy Warren (Aerospace Engineering, 2001) and Nathan Fowler (Mechanical Engineering, 2000) authored the original Experiment Safety Documentation (ESD) for the 2001 MAMMOTH Flow experiment. This author rewrote each section and all calculations in the ESD for subsequent use in the 2002 MAMMOTH Flow experiment. Figures 2.3.1 and 2.3.2 remain unchanged from Mr. Warren and Mr. Fowler's previous work. Undergraduate student Dave Garth also rendered aid in the preparation of the Pressure Vessel Certification section. Unless otherwise stated, this author composed all other sections in this paper.

In addition, the author wishes to recognize all members of the MAMMOTH Flow project for their contribution of time, energy, and vision in making this undergraduate project a success. The members of the 2001 MAMMOTH Flow experiment were UT engineering students Randy Warren, Nathan Fowler, Jeremy Smith, Timothy Craig, Jeremy Owen, Brian Babis, and Joseph Tipton. The members of the 2002 MAMMOTH Flow experiment were UT engineering students Joseph Tipton, Jeremy Smith, Brian Babis, Dave Garth, and George Hatcher. Special thanks also goes to Dr. Masood Parang for his advice and interest in helping with this project.

## **CHAPTER 1      TECHNICAL OVERVIEW**

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### **1.1      BACKGROUND**

Sponsored by NASA's Johnson Space Center, the Reduced Gravity Student Flight Opportunities Program (RGSFOP) provides a unique academic experience for undergraduate students to successfully propose, design, fabricate, fly and evaluate a reduced-gravity experiment of their choice over the course of six months. The overall experience includes scientific research, hands-on experimental design, test operations, fund-raising, educational/public outreach activities, and many other aspects of project engineering and time management. The climax of the program occurs when the selected teams come to NASA's Ellington Field for a week in Houston, TX. Here, team members have the opportunity to fly with their experiments aboard NASA's KC-135 "Weightless Wonder". Through a parabolic flight trajectory, the plane generates periods of weightlessness up to thirty seconds in length. During each forty-parabola-flight, the experiments are performed and the students are allowed to experience the excitement and wonder of weightlessness.

Currently and in the past NASA has used passive, single-phase flow systems for spacecraft thermal management. Such systems as solar collectors, fuel cells, and radioisotope generators provide power independent of gravity changes at the expense of a lower power density. Future spacecraft, orbiting stations, and space colonies will require active thermal systems for large-scale power generation. Power plants using a Rankin cycle are attractive because of the efficient heat transfer due to fluid phase changes in evaporation and condensation. These and other subsystems depend on vapor-liquid, two-phase flows for thermal management. While carrying more energy per unit mass and requiring less pumping power per unit of thermal energy than single



phase systems, two-phase thermal systems have the drawback of behaving quite differently in the microgravity conditions of space where buoyancy forces no longer exist (Carron and Best 1085). Much research has been performed on the patterns of two-phase flow in microgravity (Bousman and Dukler 174; Colin et al. 533-544; Ducker et al. 389-400; Bousman, "Studies"). In contrast, little research has been performed on heat transfer as affected by two-phase flow phase distribution in microgravity (Microgravity 145).

The affect of two-phase flow on heat transfer is best understood through heat flux, a rate defined by heat transfer divided by the area of the heating surface. As the temperature difference between the heating surface or pipe and the liquid increases, the heat flux passes through several modes of heat transfer. First, at the lowest temperature differences, the flow remains a one-phase liquid. Here, heat is transferred through natural convection along with the forced convection of the channel flow. Next, as the temperature of the heating surface increases, boiling begins to occur and small vapor bubbles are formed. The nucleation center of these bubbles is either from impurities in the fluid or from surface irregularities in the channel wall. Now the flow is a two-phase medium and natural convection along with channel flow continue to facilitate heat transfer. Finally, as the temperature difference reaches its highest levels, boiling occurs at such a rate that vapor bubbles may obstruct liquid contact with the heating surface. This phenomenon, called film boiling, creates a blanket of vapor that insulates the fluid from the heating surface. This regime of two-phased flow lowers the heat flux to a critical value, simultaneously increasing the surface temperature. Often, reaching critical heat flux destroys the heater and can melt or rupture the pipes or other heating surfaces.

Nucleate boiling provides the maximum attainable heat flux because it tends to encourage heat transfer. In a gravitational field, buoyancy forces act on the vapor

bubbles in the opposite direction of the gravity vector. Once the bubbles grow to the point that the buoyancy is greater than surface tension, the bubbles rise through the liquid and create a stirring motion. The stirring motion is advantageous in that it brings cooler liquid to the heating surface and facilitates the transfer of heat to the liquid. In reduced gravity conditions, however, buoyancy forces are much smaller and natural convection ceases to occur. In the common case where the heating surface is the pipe itself, the forced convection from channel flow also ceases to exist as the fluid flows parallel to the pipe wall keeping the bubbles in contact with the heating surface. Without the buoyancy forces created by a gravitational field, the maximum heat flux is reduced as nucleate boiling gives way to film boiling and the critical heat flux. Therefore, improving heat transfer in microgravity must be achieved through a stirring motion that sustains nucleate boiling.

Since the 1960's people have studied methods of increasing heat transfer through several methods of mixing flow including geometrical changes, force fields, and trace additives. According to Wallis, several geometrical methods to increase heat transfer have been suggested including a straight tube with short sections of larger and smaller internal diameters (Wallis and Collier, 1967). In addition, Gambill, Swenson, Matzner, and others suggest the use of ribbons and helical fining to induce swirl flow through a pipe. As explained by Tong, Wallis made the observation that changes in a flow tended to persist downstream even when changes were induced (Wallis, qtd. In Tong, 1965). Geometrical changes in an early section of pipe, therefore, would seem to continue to affect fluid flow some distance away.

Experimenting with heat transfer in fluid flow presents difficulties in microgravity conditions. Means of creating microgravity conditions through drop towers and aircraft flying parabolic trajectories create microgravity periods of only a fraction of a minute. This time period is too short to allow for measurable heat transfer from a heater surface

to a fluid. Also, safety considerations restrict the use of heating devices in aircraft and spacecraft. It therefore becomes necessary to seek means of simulating heat transfer in fluid flow.

In a lecture to an International Symposium on Research in Cocurrent Gas-Liquid Flow, Bankoff stated the importance of simulation modeling in research:

Simulation, or experimental modeling, occupies a place intermediate between that of theoretical modeling, and proof testing. It has the advantages that some over-simplified assumptions need not be made for the sake of mathematical tractability, while on the other hand, it offers considerable benefits in convenience and cost over proof testing (Bankoff 283).

In this spirit, almost every study performed to date on heat transfer in microgravity conditions has simulated heat transfer. For this proposal, the experimental apparatus uses injected air to simulate the vapor created from boiling in a forced flow. The benefit of this boiling simulation overcomes the impediments of measuring a transfer of heat in a 15-20 second test duration, simplifies the experimental apparatus, avoids unnecessary hazards, and reduces unnecessary cost.

## **1.2 TEST OBJECTIVES**

As a detailed follow-up to last year's MAMMOTH Flow experiment, the first objective of this experiment is to simulate film boiling by injecting air into a pipe with liquid flow. As the gravity level is reduced, the mechanics of the flow are expected to change resulting in the creation of a circumferential air barrier between the fluid and pipe wall.

Once this is accomplished, the second objective is to ascertain the usefulness of geometrical pipe changes in mixing the separated two-phase flow in an effort to augment heat transfer in microgravity conditions. Two devices will be tested that utilize helical ribbon and variable diameter inserts. It is believed that the helical ribbon will create a

desirable phase distribution for heat transfer applications under microgravity conditions by removing the simulated vapor barrier from the pipe wall/heating surface. Similarly, the variable diameter insert will create flow turbulence resulting in desirable mixing of the two-phases and fluid contact with the heating surface. These devices will be compared both qualitatively and quantitatively to a smooth pipe configuration to determine their usefulness in promoting heat transfer in two-phase flow microgravity conditions.

### 1.3 TEST EXPERIMENT DESCRIPTION

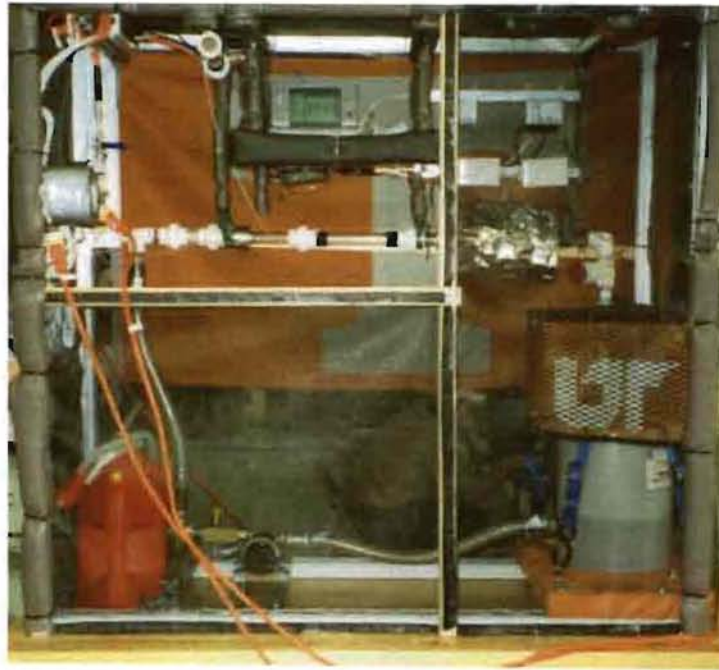


Figure 1.3.1 – The MAMMOTH Flow experiment as prepared for flight.

Figure 1.3.1 shows the completed MAMMOTH Flow experiment. The experiment apparatus is broken into four systems that are designed to operate continuously and automatically. They are fluid transfer, air injection, two-phase separation, and data acquisition. The fluid transfer section, consists of a centrifugal pump that is controlled by a precision adjustable flow regulator and feeds to a 1-inch ID clear PVC pipe. After passing through a flow straightener, the liquid passes through the air injection system.

After passing through the air injector, the flow, now a two-phase mixture, passes through a heat transfer augmentation device (HTAD) that consists of one of the geometric inserts. Threaded connections to the clear pipe allow for quick and easy exchange of the two augmentation devices and the smooth pipe replacement section. Next, the flow passes through the test section for data acquisition. Finally, the flow enters the gas-liquid separation module (GLSM) for two-phase separation. From the GLSM, liquid is fed to the pump thus closing the fluid transfer loop.

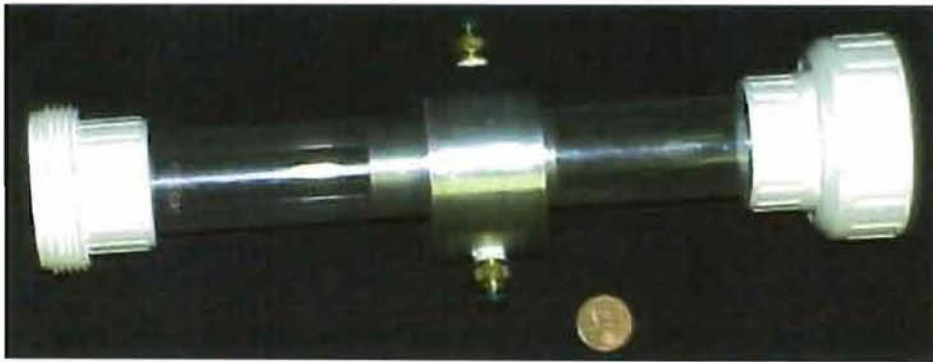


Figure 1.3.2 – The air injection system



Figure 1.3.3 – View of air injection system exit port showing circumferential injection ports on pipe wall.



The air injection system, shown in Figures 1.3.2 and 1.3.3, consists of compressed air that is injected circumferentially through a ring manifold at the pipe surface. In microgravity, this air models the vapor generation from film boiling near the pipe surface, creating a two-phase flow of liquid and gas.



Figure 1.3.4 – Two views of the Gas-Liquid Separation Module.



Figure 1.3.5 – Interior view of the Gas-Liquid Separation Module.

The two-phase separation system is designated as the gas-liquid separation module (GLSM) and is crudely modeled after the rotary fluid management device (RFMD) developed by Sunstrand and the Johnson Space Center (Microgravity 173). As shown in Figures 1.3.4 and 1.3.5, the GLSM consists of a 5-gallon HDPE container with a rotating inner cylinder that imparts centrifugal force to the gas and liquid mixture. This forces the more dense liquid to the periphery of the container, where it is fed through a pipe connection and delivered to the centrifugal pump. The less dense gas is forced toward the center of the container where it can escape via the hollow shaft that is rotating the inner cylinder. This shaft is sufficiently long to prevent any water from escaping the container.

The data acquisition system is divided into qualitative and quantitative subsystems. Qualitative data is collected through a high-speed camera positioned to view the HTAD and resulting flow. As suggested by Zhao, the camera will be selected to have a frame rate of no less than 400 frames per second (751). The quantitative subsystem utilizes a resistance heater to impart a heat flux to the flow through a steel pipe and heat sink compound. Following Rite, safety protections should include at least 50mm of high temperature ceramic fiber insulation followed by at least 20mm of thick fiberglass insulation blanket and an aluminum sheet metal casing (703). Thermocouples are placed fore and aft of the heater to measure flow temperature. A laptop computer records data from an accelerometer along with the two thermocouple voltage/temperature measurements (properly amplified by a thermocouple linear amplifier) as a function of time.

#### **1.4 TEST DESCRIPTION**

The experiment will be conducted utilizing approximately four gallons of deionized water as the liquid and compressed air as the gas. Ground testing will include

experimentally optimizing the liquid and gas flow rates and resistance heater flux. Difficulties with ground testing include the disruptive effects of buoyancy on establishing a steady vapor barrier. After the microgravity flights have occurred, the qualitative video camera results will be used to analyze how successful the experiment was at simulating a "boil-off" vapor barrier between the pipe and liquid. The quantitative measurements will be used to compare the change in fluid temperature ( $\Delta T$ ) across the heater in microgravity for the different HTAD inserts and control section. With a successful vapor barrier simulation, it is expected that the geometric HTAD inserts will increase the heat transfer from heater to fluid as compared to the smooth control section. This will be shown through the  $\Delta T$  measurements since heat transfer is a function of temperature change.

## **1.5 JUSTIFICATION FOR FOLLOW-UP FLIGHT**

The first MAMMOTH Flow experiment was accepted into the Reduced Gravity Student Flight Opportunity program and flown last year. The experiment was a success in that an apparatus was constructed that did create and attempt to measure the properties of two-phase flow. However, several areas of concern were identified with room for improvement in the final report, delivered to the Texas Space Grant Consortium program office in June, 2001.

Analysis of still photography suggested a simulated vapor barrier could be better formed by decreasing the water flow rate and modifying the air injection system to supply more air. This proposal includes redesigning the air injection system to use a ring manifold to impart only axial velocity to the air. Also, the compression spring geometric HTAD insert was shown to be ineffective in creating desirable flow mixing. Use of a full diameter width twisted (helical) tape was suggested for future testing and is



included in this proposal. Finally, the variable diameter HTAD was shown to successfully mix the two-phase flow, but the quantitative thermocouple data acquisition system failed to register a  $\Delta T$  above the error range of the measurement system. Suggestions were made to further adjust air and water flow rates and heater power. This year, the heater section will be doubled to further increase the heat flux. Also, extensive ground testing will be performed now that the apparatus has been built and tested.

In conclusion, the comments of Carson and Best about the microgravity research program learning process ring true for the MAMMOTH Flow project:

The KC-135 environment remains far from congenial for instrumentation...and inflexible when compared to most ground facilities. These unusual constraints make the learning process very unique and demanding for the experimenters (Carron and Best 1088).

The MAMMOTH Flow: Phase II team looks forward to capitalizing on the experiences of last years program entry in an effort to perform even better microgravity research.

## CHAPTER 2      EXPERIMENT SAFETY EVALUATION

---

### 2.1      STRUCTURAL ANALYSIS

The experiment framework utilizes modular T-slotted aluminum framing from 80/20 Incorporated. Six (6) NASA supplied 3/8" diameter bolts will attach the experiment framework to the KC-135's frame. The completed experiment will weigh approximately 238 lbs.

The structural analysis assumes 1) any component weighing less than 2-lbs is not included and 2) only the maximum loading case is given. Common sense mounting allows for components weighing less than 2 lbs to resist the required loads. Maximum loading cases yield the smallest safety factor; therefore, it is unnecessary to calculate lesser loads (i.e. the forward loading case of 9g is similar enough to the aft and lateral loadings that the later two need not be calculated).

#### 2.1.2      COMPONENT INFORMATION

Table 2.1.1 documents individual component weights, the overall assembly weight, and the location of the components. All bolts holding the frame together are SAE grade 5 bolts (5/16"-18). All components bolt directly to the framework via the same bolts holding the frame together. No load bearing welds exist in this experiment.

Table 2.1.1: Component Weights and Locations

Component	Weight (lbs)	Location on Frame
Frame (including hardware)	96	--
Water Pump	6	Resting on Base
Water	30	Resting on Base
GLSM	60	Supported from Base
Piping (multiple components)	15	Supported from Top of Frame
Laptop and Cradle	15	Supported from Top of Frame
Padding (multiple components)	5	All Around Frame
Surge Protector (2 ea)	4	Resting on Base
Water Containment Cylinder	1	Resting on Base
Data Acquisition System	6	Attached to Piping
<b>Total Weight</b>	<b>238</b>	

### 2.1.3 ATTACHMENT OF COMPONENTS

All following calculations use the SAE Grade 5 bolt proof strength. Calculation of the length of engagement ( $L_e$ ) determines whether the bolts will strip through the aluminum threads. The Machinery's Handbook supplies the following applicable values:

$$\begin{aligned} A_t &= 0.0524 \text{ in}^2 && \text{= tensile stress area of screw thread} \\ K_{n \max} &= 0.2524 \text{ in} && \text{= max minor diameter of internal thread} \\ E_{s \min} &= 0.2764 \text{ in} && \text{= min pitch diameter of external thread} \\ E_{n \max} &= 0.2764 \text{ in} && \text{= max pitch diameter of internal thread} \\ D_{s \min} &= 0.3125 \text{ in} && \text{= min major diameter of external thread} \\ N &= 18 \text{ tpi} && \text{= turns per inch of thread} \end{aligned}$$

$$L_e = \frac{2 \cdot A_t}{\pi \cdot K_{n \max} \cdot [0.5 + 0.57735N(E_{s \min} - K_{n \max})]}$$

$$L_e = 0.1764 \text{ in}$$

Knowledge of the length of engagement allows for calculation of the external and internal thread shear areas ( $A_s$  and  $A_n$  respectively).

$$A_s = \pi L_e K_{s \max} N \left[ \frac{N}{2} + 0.57735(E_{s \min} - K_{n \max}) \right]$$

$$A_s = 0.10482 \text{ in}$$

$$A_n = \pi L_e D_{s \min} N \left[ \frac{N}{2} + 0.57735(D_{s \min} - E_{n \max}) \right]$$

$$A_n = 0.15156 \text{ in}$$

With the thread shear areas calculated, the relative strength factor (J) of the external and internal threads becomes:

$$J = \frac{A_s \cdot UTS_{ext}}{A_n \cdot UTS_{int}} = \frac{0.10482 \text{ in} \cdot 85,000 \frac{\text{lb}f}{\text{in}^2}}{0.15156 \text{ in} \cdot 19,000 \frac{\text{lb}f}{\text{in}^2}} = 3.094$$

where  $UTS_{ext}$  is the tensile strength of the external thread material (stainless steel) and  $UTS_{int}$  is the tensile strength of the internal thread material (80/20 aluminum). Since  $J >$

1, the engagement length is not sufficient to prevent stripping of the threads. The engagement length required for prevention of thread stripping is then:

$$Q = J \cdot L_e = 3.094 \cdot 0.1764in = 0.5458in$$

Thus, an engagement length of at least 0.5458" protects against thread stripping. With thread stripping prevented, structural analysis proceeds with bolt failure calculations.

Analyzing the shear and tensile strength of a single bolt provides a concise structural analysis. Every component bolted to the frame will have at least two of the specified bolts securing it. The shear failure calculation of a single bolt begins by starting with a desired safety factor of four (4). Assuming the shear loading follows the maximum shear stress theory, where  $S_y$  equals the proof strength of the bolts:

$$S_{sy} = 0.5S_y = 0.5 \cdot 85,000 \frac{lb_f}{in^2} = 42,500 psi$$

$$SF = \frac{S_{sy}}{\tau}$$

$$\tau = \frac{S_{sy}}{SF} = \frac{42,500 \frac{lb_f}{in^2}}{4} = 10,625 psi$$

Since the minor diameter of the bolt is 0.2464in, the shear stress becomes:

$$\tau = \frac{F}{A}$$

$$F = \tau A = 0.25\pi D^2 = 0.25 \cdot 10,625 \frac{lb_f}{in^2} \cdot \pi \cdot (0.2464in)^2$$

$$F = 506.64lbs$$

Using this value as the max load at 9g, the maximum component weight is:

$$W = \frac{F}{9g} = 56lbs$$

Therefore, two bolts with a safety factor of 4 sufficiently support (in shear) any component that weights 112 lbs or less. Detailed analysis of each component in shear becomes unnecessary since no double bolted component approaches this weight.

Following the above approach, analysis continues for a failure of a single bolt in tension:

$$SF = \frac{S_y}{\sigma}$$

$$\sigma = \frac{S_y}{SF} = \frac{85,000 \frac{lb_f}{in^2}}{4} = 21,250 psi$$

Since the minor diameter of the bolt is 0.2464in, the stress becomes:

$$\sigma = \frac{F}{A}$$

$$F = 0.25 \cdot \sigma \cdot \pi \cdot D^2 = 0.25 \cdot 21,250 \frac{lb_f}{in^2} \cdot \pi \cdot (0.2464 in)^2$$

$$F = 1,013.28 lbs$$

Using this value as the max load at 9g, the maximum component weight is:

$$W = \frac{F}{9g} = 113 lbs$$

Therefore, two bolts with a safety factor of 4 sufficiently support (in tension) any component that weights 226 lbs or less. Detailed analysis of each component in tension becomes unnecessary since no double bolted component approaches this weight.

#### 2.1.4 ASSEMBLY CALCULATIONS

The frame assembly must withstand application of the required loads considering its own weight and the weight of the components attached to it. The most likely source of failure occurs from the moment induced by the top of the structure shifting forward during 9g loading. The total weight of the frame top, the laptop with cradle, the data acquisition system, heaters, and the piping equals approximately 86 lbs; however, during the 9g loading, this force becomes 774 lbs. A moment arm of 59" produces a moment of 3,805.5 ft-lbs. Failure of the bolts in the frame could possibly occur in tension, so analysis includes a 3,805.5 lbs tensile load. As stated in section 2.1.3, a single bolt

withstands a tensile load of 1,013.28 lbs with a safety factor of 4. Therefore, four bolts provide sufficient strength. Since this part of the structure utilizes four attaching bolts, no further analysis is required.

Using the same 86 lbs load for the frame above the base, the next possibility for failure occurs during the 2g up loading. As stated in section 2.1.3, a single bolt supports a component in shear that weighs 56 lbs or less in 9g loading. Thus, a safety factor greater than 4 exists for this loading scenario in 2g loading.

The final assembly failure scenario occurs in buckling. For this calculation, the support is modeled as a fixed-free end condition support. With four vertical supports, each bar would receive one-fourth of a 516 lbs load (86 lbs @ 6g downward loading). Using the moments of inertia for 80/20 extrusion, model 1515 Lite:

$$P_{cr} = \frac{\pi^2 I_x E}{(2L)^2} = \frac{\pi^2 \cdot 0.185300 \text{in}^4 \cdot 10,200,000 \frac{\text{lb}}{\text{in}^2}}{(2 \cdot 59 \text{in})^2} = 1,339.71 \text{lbs}$$

$$SF = \frac{1,339.71 \text{lbs}}{516 / 4 \text{lbs}} = 10.39$$

A safety factor of 10.39 provides adequate safety against structure buckling.

### 2.1.5 FLOOR ATTACHMENT

Floor attachment analysis depends upon the NASA supplied mounting bolts. The first calculation accounts for failure in tension. According to the JSC User's Guide, each bolt is rated for a 5000-lbs tensile load. Assuming pure tension during the 2g up load:

$$\text{Hold Down Bolt Safety Factor} = \frac{5,000 \text{lbs} \cdot 6}{238 \text{lbs} \cdot 2} = 63.0$$

This extremely large safety factor indicates the bolts will not fail in tension.

The next safety factor calculation accounts for failure in shear. If the bolts withstand shearing during the 9g forward load, they will also withstand shearing from the aft or lateral loads. Assuming pure shear during the 9g forward load:

$$\text{Shear Bolt Safety Factor} = \frac{5,000\text{lbs} \cdot 6}{238\text{lbs} \cdot 9} = 14.0$$

This large safety factor indicates that the bolts will also not fail in shear.

The final calculation determines whether the bolts could shear through the aluminum frame. Assuming pure shear during the 9g forward load:

$$\sigma_s = \frac{F}{\text{Thickness of Frame} \cdot \text{Diameter of Bolt} \cdot \text{Number of Bolts}}$$

$$\sigma_s = \frac{238\text{lbs} \cdot 9}{0.372\text{in} \cdot 0.375\text{in} \cdot 6} = 2,559.14\text{psi}$$

Since the minimum yield shear stress ( $S_{sy}$ ) for aluminum is 19,000 psi:

$$SF = \frac{19,000\text{psi}}{2,559.14\text{psi}} = 7.42$$

Therefore, the bolts will not shear through the aluminum frame.

#### 2.1.6 AIRCRAFT FLOOR LOADING

Since the load is evenly distributed along the major and minor axes, the experimental assembly will have its weight evenly distributed among the six (6) NASA supplied aluminum floor spacers. Each spacer can support a load of 200 lbs in 1g conditions.

$$\text{Load per Spacer} = \frac{238\text{lbs}}{6} = 39.67 \frac{\text{lbs}}{\text{spacer}}$$

With a load per spacer of only 40 lbs, the experiment will not violate aircraft floor loading.

### 2.1.7 SAFETY FACTOR TABLE

Table 2.1.2 summarizes the previous structural safety calculations for the MAMMOTH Flow experiment. All experimental components, when presented with their NASA required loading scenarios, present factors of safety at four (4) or above. These factors of safety are well within limits and prove the experimental structure is safe as deemed by NASA requirements.

**Table 2.1.2: Safety Factors for All Structural Analyses**

<b>Location</b>	<b>Load Case</b>	<b>Safety Factor</b>
NASA Supplied Bolts	Upward 2g	63.0
NASA Supplied Bolts	Forward 9g	14.0
NASA Supplied Spacers	Downward 6g	5.0
Frame Assembly Base (Shear)	Forward 9g	7.4
Frame Assembly Uprights Hardware (Shear)	Upward 2g	>>4
Frame Assembly Uprights Hardware (Tension)	Forward 9g	4.0
Frame Assembly Uprights (Buckling)	Downward 6g	10.39
Water Pump, GLSM, Laptop	Downward 6g	>>4



## 2.2 ELECTRICAL ANALYSIS

Figures 2.2.1 and 2.2.2 detail the set-up of the electrical system for the experimental apparatus. Figure 2.2.1 shows the voltage and amperage required by the components of the system. The system is divided into two buses, main bus A and main bus B. These buses are surge protectors with an operating voltage of 120-V<sub>ac</sub> and a maximum amperage throughput of 15-A.

Table 2.2.1 lists the required electrical loads for aircraft electrical power usage. According to this analysis, the MAMMOTH Flow experiment requires approximately 20-A of 120-V<sub>ac</sub> from the KC-135 Aircraft. Figure 2.2.2 describes the connections between the components and the aircraft power system. Currently, only one bus (Bus A) on the aircraft electrical panel will be required for operation of the experiment's electrical system.

Table 2.2.1: Load Table for Aircraft Electrical Power Usage

Power Source		Load Analysis	
Name	Bus A (B-A)	D-1	1.2 A
Voltage	120 Vac	I-1	1.5 A
Frequency	60 Hz	D-3	10.5 A
Wire Gage	12		
Current Supply	15 A	Current Draw	13.2 A
Name	Bus B (B-B)	D-2	5.4 A
Voltage	120 Vac	D-1	1.2 A
Frequency	60 Hz		
Wire Gage	12		
Current Supply	15 A	Current Draw	6.6 A
Name	Laptop Battery		
Voltage	19 Vdc		
Frequency	50-60 Hz		
Wire Gage	18		
Current Supply	3.16 A		
Name	Acceler Battery		
Voltage	9 Vdc		
Frequency	60 Hz		
Wire Gage	18		
Current Supply	0.16 A		
Aircraft Power Requirement			
		Current Draw	19.8 A

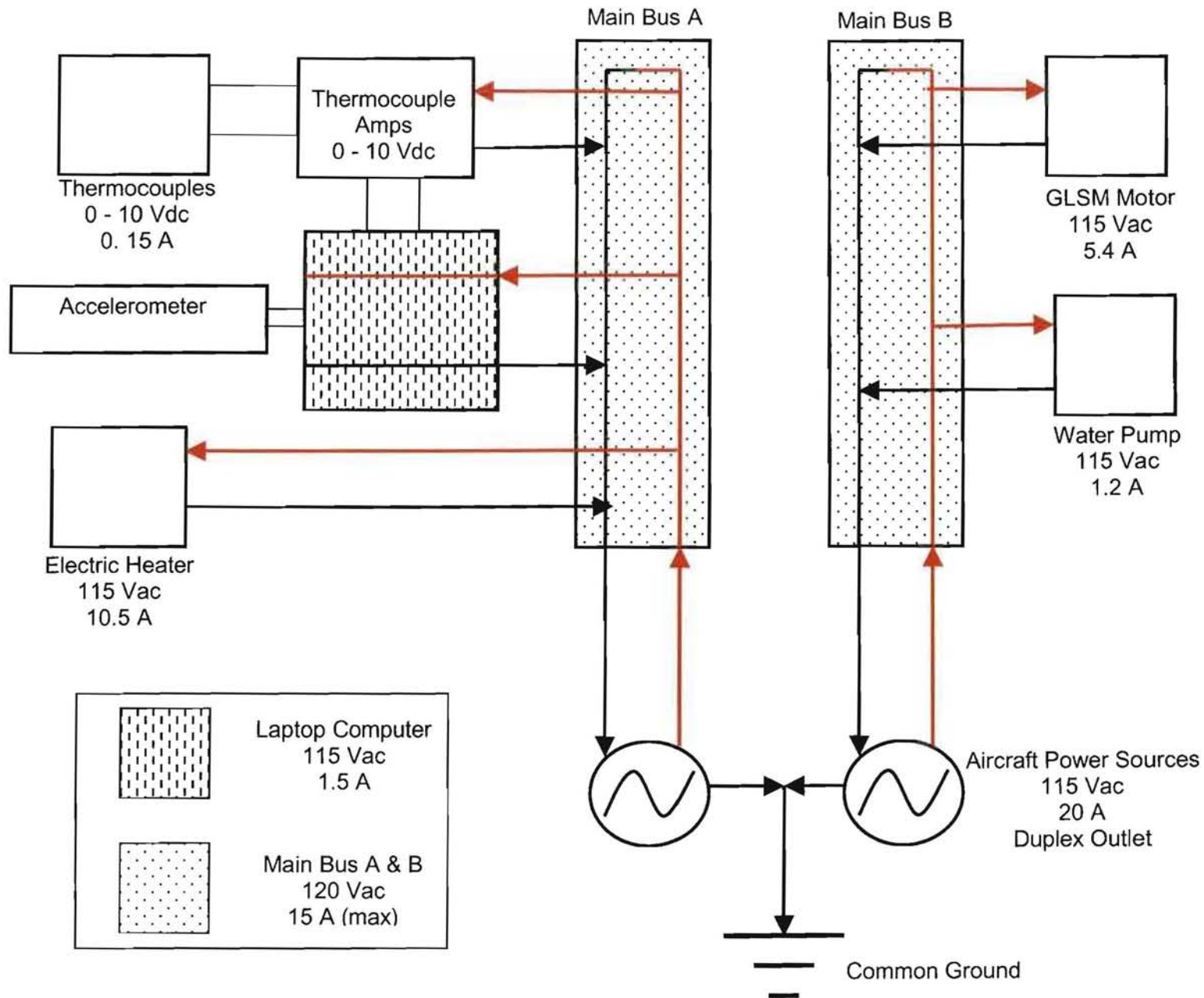


Figure 2.2.1: Circuit Diagram for Experimental Apparatus

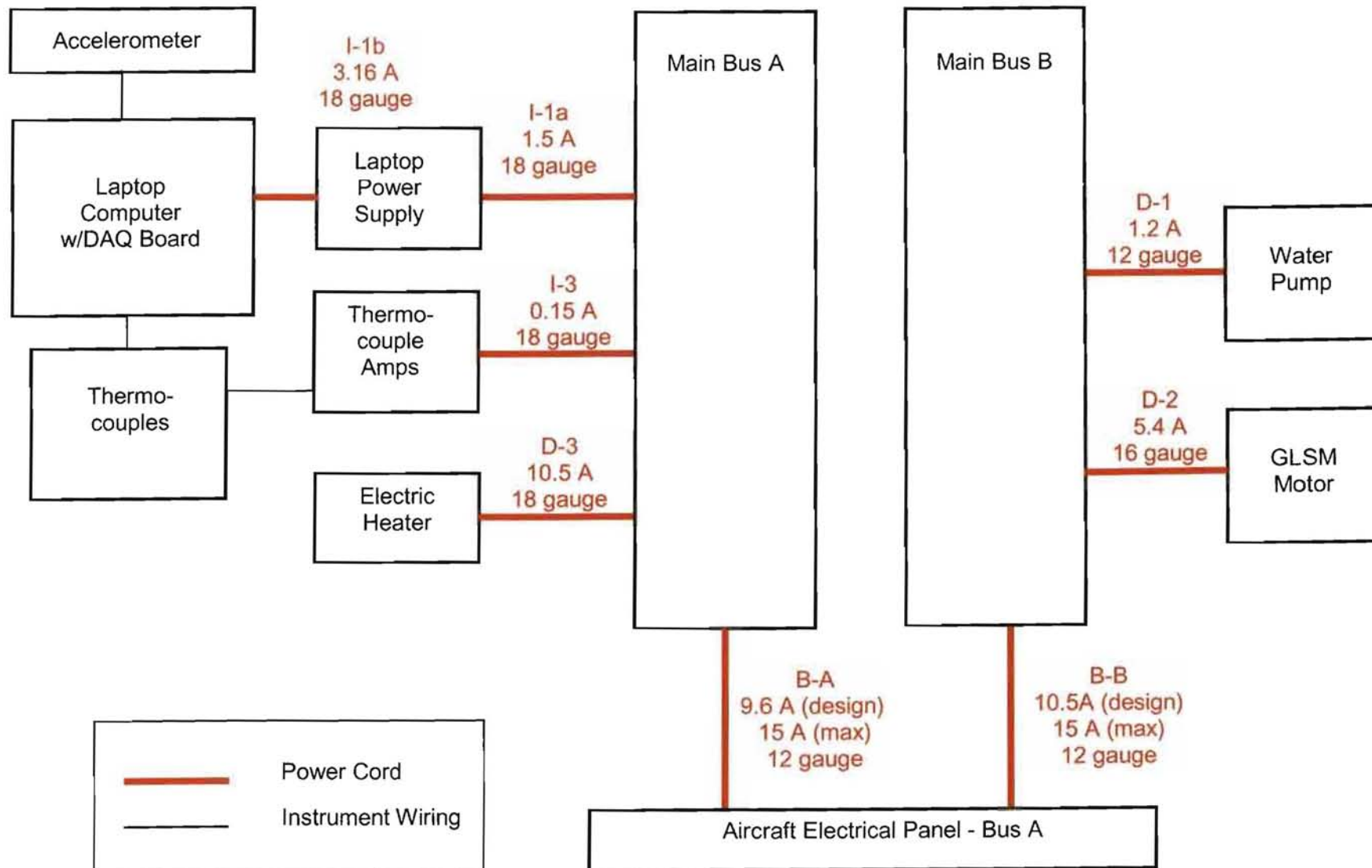


Figure 2.2.2: System Wiring Specifications and Nomenclature

### *2.2.2 EMERGENCY SHUTDOWN PROCEDURE*

The experimental apparatus will be equipped with an emergency “kill” switch that will disconnect the experiment electrical system from the aircraft power supply. This switch will be located next to the laptop computer and within easy reach of a member of the flight crew. When the “kill” switch is activated, the system returns to its safe mode, such that all power to the system components is disconnected.

Once the system is disconnected, the flight crew members will switch all individual systems to their respective “off” modes. Prior to any reactivation of the system, a complete visual inspection will be performed to ensure all systems are “off” and that no damage has occurred that would preclude operating the system.

## 2.3 PRESSURE VESSEL CERTIFICATION

This experiment contains two pressurized systems that are composed primarily of ANSI certified materials, including pipes, fittings, and hoses. All construction utilizes accepted methods. The air injection system is a Category D pressure system while the actual water piping system is a Category E pressure system due to its inherently low energy operation (below 150-psig and 110°F). Schematics of both systems are shown in Figures 2.3.1 and 2.3.2.

The water piping system will be constructed using solvent welded Schedule 40 and Schedule 80 rated pipes and fittings, and will operate with a maximum allowable working pressure (MAWP) of 6.5 -psig, which is the highest value available from the pump. With this value in mind, the entire water and air assembly design has been evaluated and calculations performed with the component subjected to a pressure of 1.25 times the maximum allowable working pressure. The component with the lowest value for a pressure rating was the threaded PVC to metal connections, with a Schedule 80 pressure rating derated by 50%. This condition results in a component ultimate pressure rating of 315-psi. Using the aforementioned pressure rating, the water-housing factor of safety is 38.8, which is much greater than the required value of 4. This number is high due to the low MAWP of 6.5 psig. The calculations that led to the determination of this safety factor are as follows:

### PUMP SPECIFICATIONS:

$$\begin{array}{ll} \text{Work Rate} & W_r = 137.5 \frac{\text{lb} \cdot \text{ft}}{\text{sec}} \\ \text{Flow Rate} & Q = 0.00958 \frac{\text{ft}^3}{\text{sec}} \\ \text{Head} & \Delta z = 2 \text{ ft} \end{array}$$

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + h_{\text{pump}} + \Delta h_{\text{loss}}$$

$$P_1 = \rho g (h_{\text{pump}} + z_2) = 62.4 \frac{\text{lb}}{\text{ft}^3} (12.1 \text{ ft} + 2 \text{ ft}) = 879.84 \text{ psfg} = 6.11 \text{ psig}$$

$$MAWP = 6.5 \text{ psig}$$

$$\sigma_{ult} = 630 \text{ psi} \cdot 0.5 = 315 \text{ psi}$$

$$\text{Housing Factor of Safety} = \frac{\sigma_{ult}}{\sigma_{MAWP}} = \frac{315 \text{ psi}}{6.5 \text{ psi} \cdot 1.25} = 38.8 > 4$$

The air injection system involves a Category D pressure system and will utilize two pressure relief valves set to a maximum allowable working pressure of 35-psi. The relief valves will be connected directly to the air supply on the inlet, and will be connected to 50-feet of 0.25", ANSI certified air hoses, and connections with pressure ratings to 200-psi. Using the method previously presented, the factor of safety for the aluminum air injection system was calculated to be 800, which is well over the required factor of safety of 4. This number is so high because the purpose of the air injection system is not to add pressure to the system, but to change the injection of air from an orthogonal insertion to multiple parallel injections close to the inner wall of the pipe.





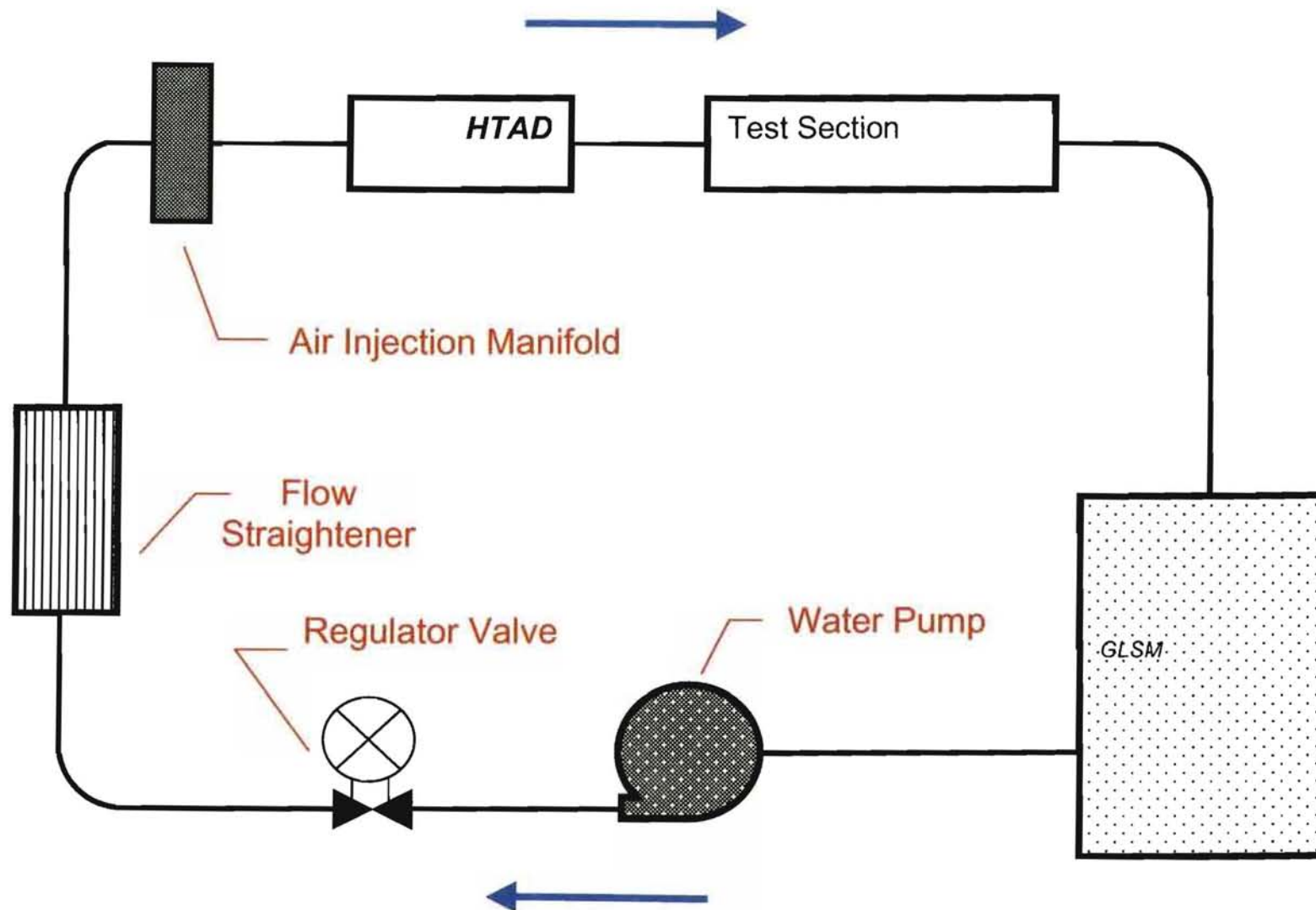


Figure 2.3.2: Water System Pressure Vessel Schematic



## 2.4 HAZARD ANALYSIS

Table 2.4.1: Hazard Identification Table

Detail ID #	Identified Possible Hazards
N/A	Flammable/combustible material, fluid (liquid, vapor, or gas)
1	<b>Toxic/noxious/corrosive/hot/cold material, fluid (liquid, vapor, or gas)</b>
2	<b>High pressure system (static or dynamic)</b>
N/A	Evacuated container (implosion)
N/A	Frangible material
N/A	Stress corrosion susceptible material
3	<b>Inadequate structural design (i.e., low safety factor)</b>
N/A	High intensity light source (including laser)
N/A	Ionizing/electromagnetic radiation
4	<b>Rotating device</b>
N/A	Extendible/deployable/articulating experiment element (collision)
N/A	Stowage restraint failure
N/A	Stored energy device (i.e., mechanical spring under compression)
N/A	Vacuum vent failure (i.e., loss of pressure/atmosphere)
N/A	Heat transfer (habitable area over-temperature)
5	<b>Over-temperature explosive rupture (including electrical battery)</b>
6	<b>High/Low touch temperature</b>
7	<b>Hardware cooling/heating loss (i.e., loss of thermal control)</b>
N/A	Pyrotechnic/explosive device
N/A	Propulsion system (pressurized gas or liquid/solid propellant)
N/A	High acoustic noise level
N/A	Toxic off-gassing material
N/A	Mercury/mercury compound
N/A	Other JSC 11123, Section 3.8 hazardous material
N/A	Organic/microbiological (pathogenic) contamination source
8	<b>Sharp corner/edge/protrusion/protuberance</b>
N/A	Flammable/combustible material, fluid ignition source (i.e., short circuit; undersized wiring/fuse/circuit breaker)
9	<b>High voltage (electrical shock)</b>
N/A	High static electrical discharge producer
N/A	Software error
N/A	Carcinogenic material
N/A	Other

Hazard Number: 1

Title: Toxic/Noxious/Corrosive/Hot/Cold Material, Fluid (liquid, vapor, or gas)

Hazard Description:

Because we are circulating distilled water through the system, there are many pipe/hose connections that are critical to the experiment. The fluid in this system will also be heated to temperatures approaching the JSC touch temperature limit of 122°F. A possibility exists that a connection could break apart or come loose, causing heated water to leak from the system. This would pose danger to members of the crew.

Hazard Cause(s):

- 1) Inadequate design
- 2) Accidental breakage (hit with elbow, kicked)

Hazard Control(s):

From the design, all piping will be located centrally in the superstructure frame. This will minimize the potential for accidental breakage. All piping/tubing will meet industry standards. All joints will be properly sealed and checked for leakage before flight. If a leak does occur, operational procedures are in place to remedy the problem.

Hazard Number: 2

Title: High Pressure System (static or dynamic)

Hazard Description:

This experiment involves the use of pressurized air. There is a possibility that the air injection system could fail, in turn over-pressurizing the experimental apparatus. This could result in an explosion of the experimental system.

Hazard Cause(s):

- 1) No pressure relief valve attached to air injection system
- 2) Pressure relief valve failed to open at the correct pressure

Hazard Control(s):

Two pressure relief valves (check valves) will be attached to the pressurized air canisters. These valves will be set to discharge excess air at 35 psi. All of the tubing and piping of the system has been designed to withstand the addition of extra pressure to the system.

Hazard Number: 3

Title: Inadequate Structure Design (Low Safety Factor)

Hazard Description:

In the event of the failure of the superstructure, the experiment would collapse. If a collapse would occur, the experiment would fail as well. There would be a risk to the crewmembers because of floating debris and liquid in the cabin.

Hazard Cause(s):

- 1) Failure to tighten all fastening bolts on the structure
- 2) Fastening bolts were over tightened
- 3) Excessive loading to the structure

Hazard Control(s):

Numerous measurements were made during the design process to ensure that failure would not occur. They may be found in Chapter 6, Section 8 (Structural Load Analysis). All materials that are to be used will meet industry standards.

Hazard Number: 4

Title: Rotating Device(s)

Hazard Description:

A vital component to our experiment is the Gas and Liquid Separation Module (GLSM). This system is to rotate about its central axis at approximately 1725 revolutions per minute.

Hazard Cause(s):

- 1) Loose clothing can become caught in the device.
- 2) Body parts (fingers, hair, etc.) can become tangled in the device.
- 3) Any floating debris can become tangled in the device.

Hazard Control(s):

All rotating parts (belts, shafts, etc.) will be shielded by a guard to prevent any foreign objects from entering the area as well as to prevent injury to the crewmembers. The experiment is to be equipped with a "kill switch". If debris or body parts become entangled in the device, the switch is to be turned off, and the entire electrical system will be shut down.

Hazard Number: 5

Title: Over-Temperature Explosive Rupture

Hazard Description:

Our experiment makes use of an accelerometer, which is powered by three (3) 9-volt batteries. These could potentially over-heat and in turn rupture.

Hazard Cause(s):

- 1) Defective battery from manufacturer.
- 2) Overheating from external sources (pump, heater, etc.)

Hazard Control(s):

Each battery will be visually inspected for abnormalities. These batteries will also be kept away from any form of external heating. In the event that one of these batteries should explode, the "kill switch" will be pressed, and the system will be powered off. A member of NASA's flight crew will immediately be notified.

Hazard Number: 6

Title: High/Low Touch Temperature

Hazard Description:

Our experiment consists of three (3) mineral-insulated resistive band heaters that will be used to impart heat to the water flow. Water overheat or loss of water flow would cause the heater to reach its maximum design temperature of 1400°F. If allowed to operate at this condition for a prolonged period, the insulation system might fail resulting in human touch temperatures above the 120°F limit.

Hazard Cause(s):

- 1) Heaters accidentally left on when not in use.
- 2) Breakdown of thermal insulation

Hazard Control(s):

The heating elements will be covered with 2 inches of ceramic fiber blanket rated to 2300°F. The ceramic fiber blanket will then be wrapped in 1 inch of high-temperature fiberglass blanket rated to 1000°F. Finally, the insulation blankets will be wrapped in aluminum tape. To guard against overheating, the heating system will only be run at 5 minute intervals, while playing close attention to the heat load. In the event of water overheat or loss of water flow, the heater will immediately be shut down.

Hazard Number: 7

Title: Hardware Cooling/Heating Loss (Loss of thermal control)

Hazard Description:

With use of our three (3) mineral-insulated resistive band heaters, there is a possibility that the thermal control could be lost.

Hazard Cause(s):

- 1) Accidentally moving thermal controller to maximum output.
- 2) Unresponsiveness in thermal control switches

Hazard Control(s):

If these heaters were to begin heating uncontrollably (either by accident or mechanical failure), the "kill switch" would be pressed to shut the entire system off. If this occurs with a specific heater, it can be shut off independently of the other two (2) heaters.

Hazard Number: 8

Title: Sharp Corner/Edge/Protrusion/Protuberance

Hazard Description:

The superstructure is to be made of extruded aluminum beams. It is in the shape of a rectangular box; with four (4) exposed potentially sharp corners, and numerous ninety-degree (90°) angles of the beams.

Hazard Cause(s):

- 1) Nature of design, with 90° angles used.

Hazard Control(s):

All of the exposed aluminum will be shielded by foam rubber padding. Extra padding will be placed on the four (4) corners to prevent any protrusion of these sharp junctions.

Hazard Number: 9

Title: High Voltage (Electrical Shock)

Hazard Description:

Our experiment will be using several electrical devices (pumps, motors, computers, etc). With this, the possibility exists that a crewmember can be shocked.

Hazard Cause(s):

- 1) Frayed wires/cables
- 2) Improper connections at electrical interfaces.
- 3) Uncovered power strip outlets

Hazard Control(s):

Our experiment will be equipped with a surge protector. The electrical system will be run through this safeguard. It has a built in circuit breaker and will shut down in the event of a power surge through the aircraft. A "kill switch" will be provided to press in the event of an emergency. Before the flight, all electrical cords/cables will be inspected and replaced or corrected if deemed necessary. All unused power strip outlets will be plugged with a plastic stopper to prevent the entry of any foreign objects.

## 2.5 EXPERIMENT PROCEDURES DOCUMENTATION

### 2.5.1 GROUND OPERATIONS

The experiment apparatus will be constructed and tested by both MAMMOTH Flow flight and ground crew members upon arrival at Ellington Field. Team members shall observe the following procedures during construction and testing of the apparatus prior to flight:

- 1) **Construction of the superstructure** – The supporting extruded aluminum frame will be fully erected and all mounts will be tested to ensure proper fitting with the aircraft floor. Once mounted, the structure will be pull-tested to ensure it meets the required safety levels.
- 2) **Mounting of system components** – Each component will be mounted to the structure and pull-tested to ensure proper mounting. Once all components are mounted, the structure will undergo another pull-test.
- 3) **Electrical connections of components** – Once all components are properly mounted, all electrical connections will be made. Each system will then be tested individually to ensure proper connections have been made.
- 4) **Full power electrical testing** – Once each component has been verified as properly connected, the entire system will be powered up simultaneously. During this testing, the “kill” switch will also be tested to ensure that it is in working order.
- 5) **Fluid system testing** – Upon successful completion of the full power electrical test, the deionized water will be introduced to the system and testing will be conducted on all pipe fittings and measurement systems.
- 6) **Air injection testing** – Once the fluid system is functional, the air injection system will be brought on line and tested to ensure that proper pressures are reached and maintained. The GLSM will also be evaluated to ensure proper operation.
- 7) **Full system test** – Once all systems are operational, a complete series of test cycles will be run and data will be collected. This data will then be compared to data collected prior to arrival at Ellington Field.

### **2.5.2 GROUND SUPPORT REQUIREMENTS**

Ellington Field should supply the following for ground support of the MAMMOTH

Flow experiment:

- 1) Power - 115 VAC, 60 Hz, 20.1 A
- 2) K-Bottles - A total of three (3) breathing air canisters. (Two for ground testing and two for flight testing.)
- 3) Deionized water – Approximately 3.5 gallons
- 4) Access to hangar tools including 'twist tie' gun.

### **2.5.3 LOADING**

The total weight of the experimental assembly is 238 lbs. While on the ground, the experiment rests on four (4) pneumatic casters. Assuming an even load distribution, the weight of 238 lbs yields an average of 59.5 lbs per wheel. The use of six (6) handles on the experiment allows for manipulation and lifting of the experiment. Assuming a maximum experiment weight of 300lbs and one person per handle, the experiment lifting load stays at or below the maximum 50lbs/person JSC requirement. MAMMOTH Flow: Phase II requires a forklift and loading pallet to load the apparatus onto the aircraft. As stated in Section 2.1.6, six (6) supplied aluminum floor spacers shall secure the experiment to the aircraft floor. With the base dimensions of 62.5" L x 23.0" W, there is a total base plate area of 9.98 ft<sup>2</sup>. The average load on the aircraft floor is then 23.85 lb<sub>f</sub>/ft<sup>2</sup>.

### **2.5.4 PRE-FLIGHT**

The pre-flight checklist is similar to the ground operations procedures. Once the apparatus is secure on the aircraft, the flight crew begins power-up procedures and fluid system testing. One full test run is conducted with the apparatus on full aircraft power

prior to take-off. Once all systems are verified, the system is powered down and all tools stowed for take-off.

#### **2.5.5 TAKE-OFF / LANDING**

Take-off and landing procedures are the same. The experiment is powered down and all items secured. After take-off, once the aircraft reaches cruise altitude, the in-flight start-up procedures are implemented.

#### **2.5.6 IN-FLIGHT**

Initially, the MAMMOTH Flow experiment begins with the clear section HTAD control insert. During flight, all systems run continuously until the halfway point. At this point, the plane returns to level flight and begins a 3-5 minute turn. During this time, the experiment is shut down, the control section is replaced with an HTAD insert, and the system is restarted following procedures. All in-flight procedures are listed below.

MAMMOTH Flow: Phase II does not require any special assistance from the Test Directors before, during, or after flight.

### **START-UP PROCEDURES**

1. Ensure all gate valves are set in their proper positions.
2. Ensure main power switch and both power strips are in "OFF" position.
3. Ensure Heaters are turned OFF.
4. Switch main power switch to "ON".
5. Switch Bus A to "ON".
6. Start laptop computer.
7. Switch accelerometer to "ON".
8. Open air supply to air injection system.
9. Remove stopper from GLSM.
10. Switch Bus B to "ON".
11. Open "master.vee" file on computer.
  - a. Check for proper data acquisition.
  - b. Trim accelerometer gain to 1-g.
  - c. Activate "Autocollection" switch.



## **SHUT-DOWN PROCEDURES**

1. Turn both heaters to "OFF".
2. Shut down laptop computer.
3. Switch main power switch to "OFF".
4. Place stopper on GLSM vent.
5. Shut off air supply.
6. Shut down laptop computer.
7. Reset all switches/valves to pre-startup positions.
8. Turn off accelerometer.

## **DATA COLLECTION**

1. Switch both heaters to "ON".
2. Place both slides to far RIGHT position.
3. Ensure a  $\Delta T$  is recorded.
4. When fluid temperature reaches 120°F, switch both heaters to "OFF".

## **EMERGENCY SHUT-DOWN (CATASTROPHIC LEAK)**

1. Switch main power switch to "OFF".
2. Stop any immediate spills with corks and towels.
3. Notify flight crew of problem and request return to 1-g.
4. Shut off air supply.
5. Unplug GLSM from Bus B.
6. Switch Bus A to "OFF".
7. Connect dump hose to pump outlet.
8. Open water dump valve / Close loop valve.
9. Switch main power switch to "ON" until pump has transferred water into secure container.
10. Close water dump valve.
11. Transfer remaining GLSM liquid to secure container via hand pump.
12. Secure all containers and clean up remaining spills with hand towels.

### **2.5.7 POST FLIGHT**

Preparation for the next day's flight includes replenishment of the deionized water and replacement of the K-bottles used for the air injection system.

### **2.5.8 OFF-LOADING**

The process for off-loading the apparatus is the reverse of the same process found in the loading section.

## CHAPTER 3 DATA ANALYSIS

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### 3.1 QUALITATIVE ANALYSIS

Unfortunately for the experiment, time and money limitations did not allow for the use of a high-speed digital camera as was stated in Chapter 1. Instead, a still camera was used to record images of the flow during periods of microgravity. Additional problems arose from the vibrations that occurred during the flight. These vibrations shook the camera making some pictures fuzzy. All clear pictures were taken from a free-floating camera. Figures 3.1.1 and 3.1.2 show the smooth pipe control section in microgravity conditions. Figure 3.1.1 is especially interesting because it includes visualization of the air/water mixture at the exit of the air injection system. Close inspection of these two photographs show a core flow of air surrounded by a thin water film which was the opposite of this experiment's goal.



Figure 3.1.1 – Smooth pipe control section and air injection system in microgravity conditions.



Figure 3.1.2 – Smooth pipe control section in microgravity conditions.

Figure 3.1.3 shows why this condition occurred despite efforts to create the opposite. The clear section of tube shown after the air injection system is approximately four (4) inches in length. At the exit of the air injector, there is a core of water surrounded by a film of air. In the course of those four inches, the air has already been displaced from the pipe wall towards the center of the pipe. Obviously, surface tension effects played a much larger role than expected and did not allow for the stable formation of an outer air sheath with a water core flow.



Figure 3.1.3 – Water and air displacement immediately after passing through the air injection system.

Figures 3.1.4 and 3.1.5 show the turbulence promoter and twisted tape Heat Transfer Augmentation Devices (HTAD) in microgravity conditions respectively. While the devices, as explained above, were not operating in the designed condition, they none-the-less both appear to provide sufficient mixing enhancement of the two-phase flow. This is indicated by the high degree of mixture between air and water shown by the small air bubble sizes and thorough bubble dispersion. It is theorized that, in the presence of a reversed water/vapor barrier, these two devices would be suitable for increasing flow mixing and therefore heat transfer.



Figure 3.1.4 – Turbulence promoter HTAD in microgravity conditions.



Figure 3.1.5 – Twisted tape HTAD in microgravity conditions.

### 3.2 QUANTITATIVE ANALYSIS

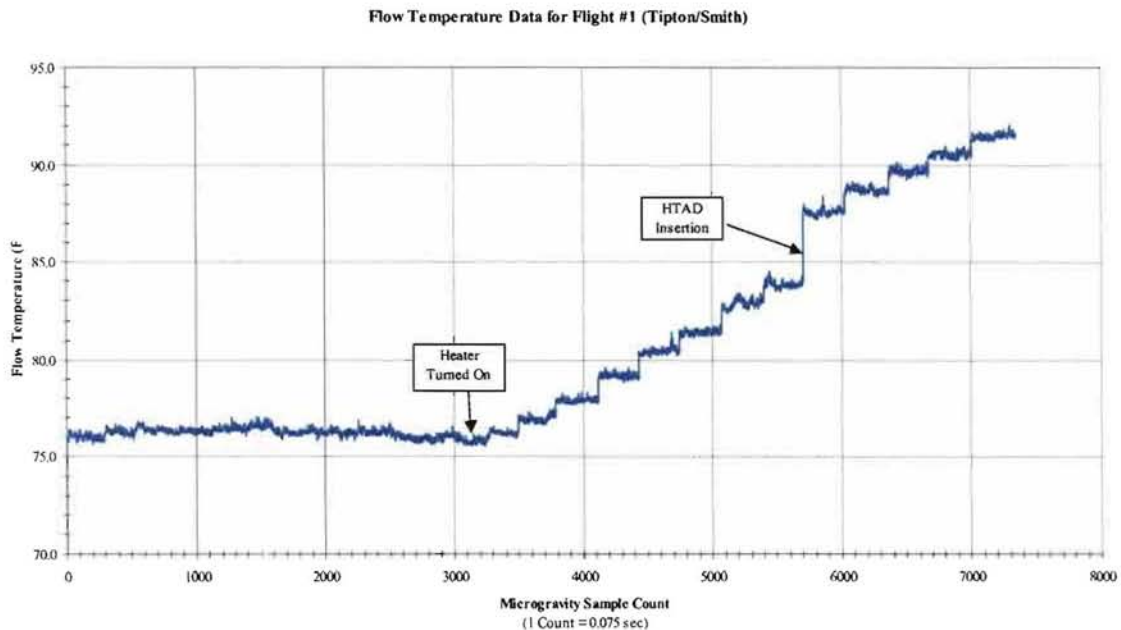
As stated in the test experiment description in section 1.3, the qualitative data collection system consisted of a normal acceleration measurement, a flow temperature measurement, and a temperature difference measurement across the heater section. The temperature measurement instruments consisted of two thermocouple rakes positioned at the fore and aft of the heater section. Each thermocouple rake consisted of four thermocouples placed at quarter intervals around the pipe. The tips of each thermocouple protruded approximately one-sixteenth of an inch from the pipe ID into the flow stream. For the flow temperature measurement, the fore thermocouple rake was sent through a linear thermocouple amplifier which averaged the four thermocouple measurements and amplified the results. For the temperature difference measurement across the heater section, both the fore and aft thermocouple rakes were sent through a second linear thermocouple amplifier. This amplifier was arranged to average the four thermocouples in each rake, take the difference between the two rakes, and then amplify this difference. Laboratory testing ensured proper calibration of the thermocouple/amplifier systems before installation onto the experimental apparatus.

The HP VEE data acquisition system was used to record the three measurements with time. The best resolution possible for continuous measurements



was approximately 0.075 seconds. While the program continuously displayed these measurements in real time for the experimenter's information, only measurements taken below 0.5 g were recorded to conserve file space.

The first microgravity flight occurred on the afternoon of Thursday, March 28, 2002. The flight consisted of thirty microgravity parabolas. The experiment was run and data was recorded for twenty-four of these parabolas. For the first thirteen of the twenty-four recorded parabolas, the smooth pipe control section was in place and the heaters were off. For the next eight recorded parabolas, the smooth pipe control section was kept in place and the heaters were activated. For the final five recorded parabolas, the heaters were kept on and the smooth pipe control section was replaced with the turbulence promoter insert (HTAD A). Figure 3.2.1 shows a plot of the flow temperature versus time count for all twenty-four parabolas. The plot reveals the point in time at which the heaters were activated as shown by the steady increase in flow temperature.



**Figure 3.2.1 – Flow temperature versus time count for microgravity parabolas in flight #1.**

### Collected Temperature Change Data for Flight #1 (Tipton/Smith)

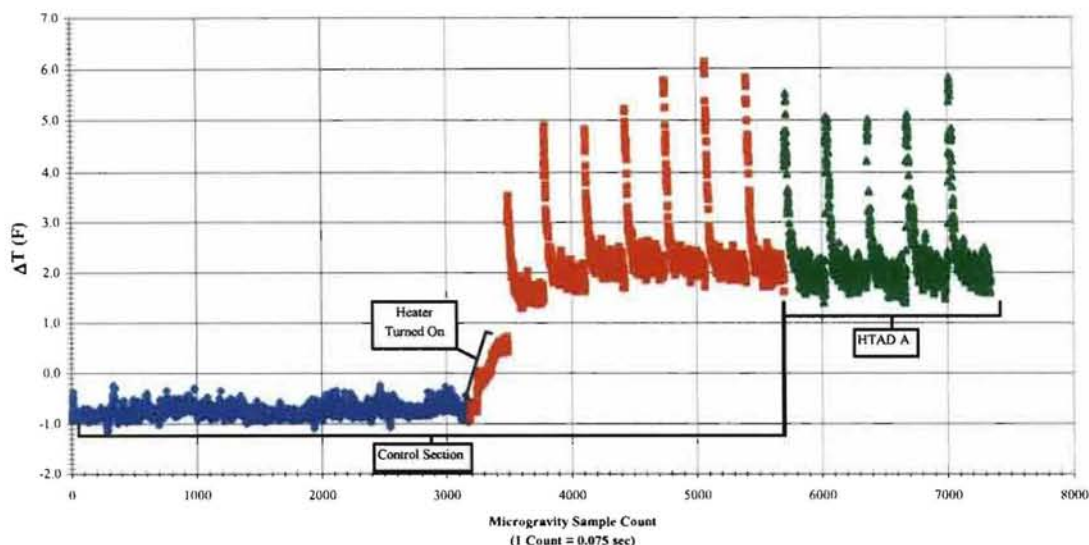
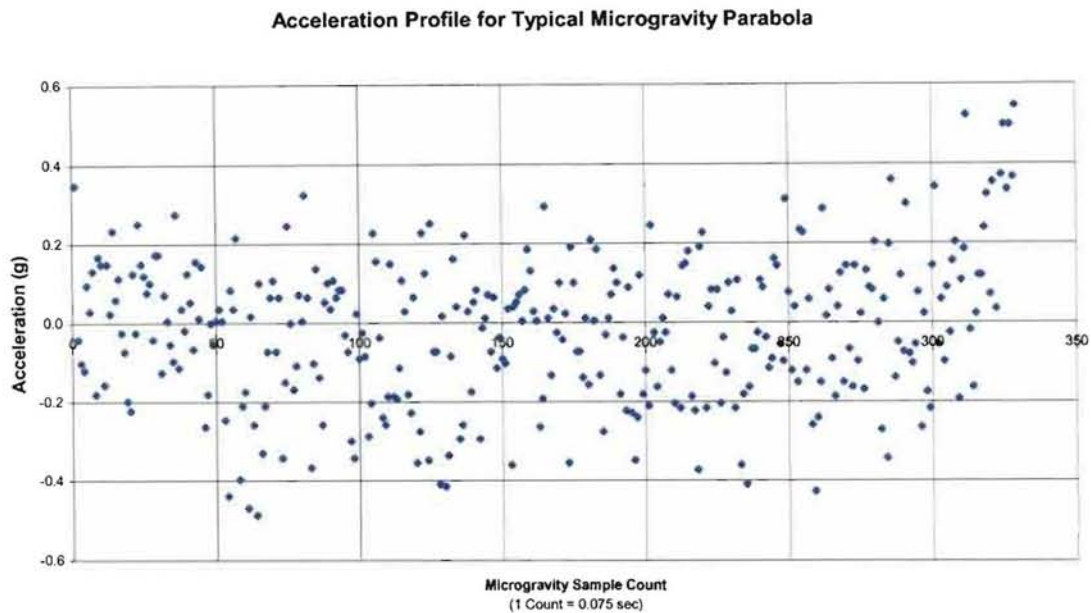


Figure 3.2.2 – Temperature change vs. time count for microgravity flight #1.

Figure 3.2.2 reports the temperature change versus sample count for the twenty-four recorded samples. This figure reveals several items of interest. First, the baseline measurements for the control section with heaters off shows an average temperature difference of  $-0.734671^{\circ}\text{F}$  which represents an error in the zero measurement. Addition of  $0.734671^{\circ}\text{F}$  to all data would properly calibrate the measurements to a true baseline measurement of zero temperature change. Also of interest in the figure is the response time in temperature difference measurements after activation of the heater. A transient period existed that spanned three parabolas in length during which the heater reached full power. The data collected in these three parabolas does not match the last five parabolas for the control section and should be disregarded in further calculations. Finally, Figure 3.2.2 shows an interesting phenomenon for each parabola in which the heaters were active. A spike in the temperature difference measurement occurs at the beginning of each parabola and then quickly diminishes. This spike was reproduced on the ground when physical pressure was placed on the computer, apparently creating an

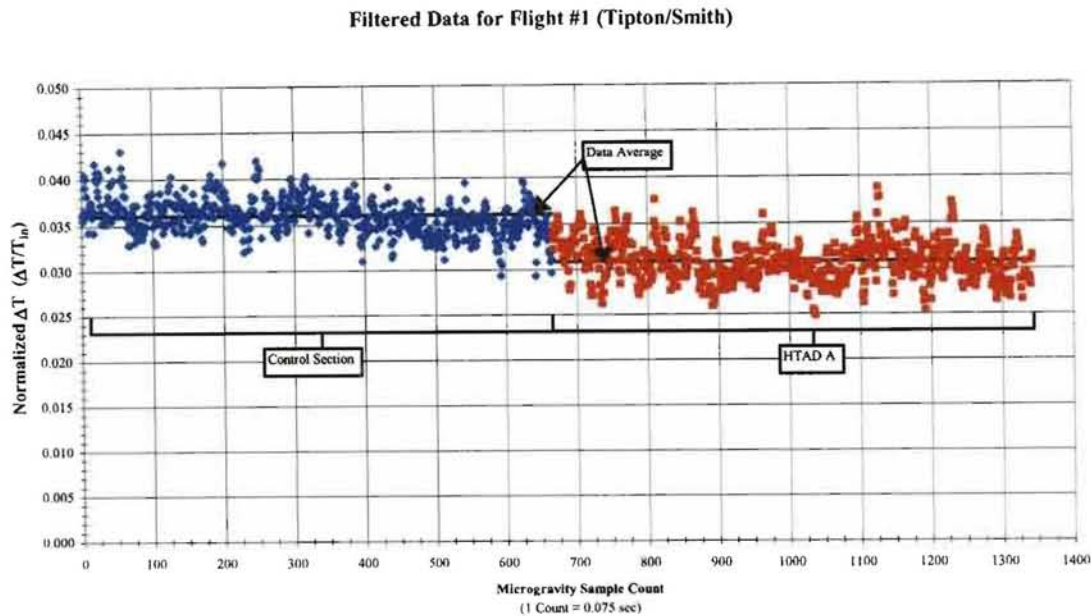
electrical short of some type. Since the aircraft experienced a constant 1.8 g loading in between microgravity parabolas, the increased force upon the computer activated the short and thus created the faulty measurements.



**Figure 3.2.3 – The recorded normal accelerations for an average microgravity parabola.**

Figure 3.2.3 represents the apparent gravity measurements made by the accelerometer for an average microgravity parabola aboard the KC-135. The g-jitter experienced from aircraft vibration limits the accuracy of the accelerometer measurements to  $\pm 0.5$  g. In an effort to use only data from true periods of microgravity ( $\pm 0.2$  g), only the middle 10 seconds of data for each parabola should be used. This also clips the incorrect temperature difference spike in each parabola as discussed previously.





**Figure 3.2.4 – Filtered and normalized temperature difference measurements versus time count for flight #1.**

Figure 3.2.4 represents the resulting filtered and normalized data for flight #1. In this plot, all temperature difference measurements were increased by  $0.734671^{\circ}\text{F}$  to correct the error in the zero measurement. In an effort to normalize the data, the resulting temperature difference measurements were then divided by the flow temperature at each point in time. In addition, this figure shows only the middle ten seconds of data collected for each parabola for reasons previously stated. The results indicate an average normalized temperature difference of 0.035992 for the smooth pipe control section and 0.030876 for the turbulence promoter (HTAD A) insert. Since the temperature difference across the heater is directly related to the heat transfer, the Heat Transfer Augmentation Device seems to actually decrease heat transfer to the flow when compared to the control section. In actuality, this is not the case.

As shown by the qualitative analysis in Section 3.1, the experiment did not succeed in creating an outer air film around a central water core. Instead, the water immediately displaced the injected air and adhered to the surface of the pipe. Since the

thermocouples protruded only one-sixteenth of an inch into the pipe, they recorded only the water temperature for the control section. Once the turbulence promoter insert was introduced, however, the thermocouples now measured the temperature difference across the warm water after it was thoroughly mixed with the room temperature injected air. Thus, the resulting temperature difference measurement was lower than that for the control section.

The second microgravity flight occurred on the morning of Friday, March 29, 2002 and tested the turbulence promoter insert (HTAD B). Unfortunately, due to unforeseen problems during the flight, no baseline data from the control section was recorded. Therefore, no useful analysis can be compared in an effort to ascertain the usefulness of the insert in increasing heat transfer.

In conclusion, the experiment failed to produce the desired flow scenario. The basic premise behind the experiment remains strong, however, and good data acquisition has allowed for a complete analysis of the data from the microgravity flight. By learning from the problems and by capitalizing on the successes seen in this analysis, the MAMMOTH Flow experiment should present a continuing yet rewarding challenge for next year's Reduced Gravity Student Flight Opportunity Program at UT.

## CHAPTER 4     OUTREACH

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The University of Tennessee owes its participation in the NASA Reduced Gravity Student Flight Opportunity Program (RGSFOP) to the vision and dedication of aerospace engineering graduate Randy Warren. While he was a junior at UT in 2000, Randy founded the Aerospace Education and Research Organization (AERO) on campus. AERO has two main purposes: to provide valuable education and research opportunities in aerospace activities to all students of the University of Tennessee, Knoxville and to educate the local community about the importance of aerospace research and development. Randy also recruited Dr. Larry Taylor as the AERO faculty advisor. As head of the Planetary Geological Institute and the Tennessee Space Grant Consortium at UT, Dr. Taylor has provided the vision, leadership, and funding for AERO and its projects.

With the graduation of Mr. Warren in 2001, the author became AERO president for the 2001-2002 school year. Along with the duties as project leader for MAMMOTH Flow, the author implemented several activities to fulfill AERO's overall mission of outreach to the public and to the university. The first step involved creation of an official web site for AERO at <http://web.utk.edu/~aeroutk/>. This website provides information on all of AERO's activities including a synopsis of UT's participation in the 2001 and 2002 RGSFOP.

Outreach to the students at UT began with the design of an electric information kiosk for display in the main floor of the Dougherty Engineering building. At the time of this writing, the kiosk's Power-Point program has been completed and delivered and is awaiting installation by department personnel. Also, an article about AERO and UT's participation in the RGSFOP was written for the Daily Beacon student newspaper (see

Appendix C). Finally, AERO hosted an entry for MAMMOTH Flow in the UT Exhibition of Undergraduate Research and Creative Achievement Fair in April, 2002. At this fair, the UT student body and visiting high school classes had the opportunity to review information, flight footage video, and technical results from the MAMMOTH Flow experiment. This entry subsequently received an Engineering Award for Excellence from the Fair Judges (see Appendix D).

Outreach to the local community has spanned all age groups. In October 2001, AERO hosted a booth for Engineer's Day at the UT campus. During the course of the day, middle and high school students visited and received presentations regarding AERO and the microgravity research experiences afforded to undergraduate college students. Figures 4.1 and 4.2 show students from an area middle school science class touring this information booth.



Figure 4.1 – Students from Alcoa Middle School tour an information booth about MAMMOTH Flow during Engineer's Day 2001.



Figure 4.2 – Students from Alcoa Middle school view a presentation by the author with flight footage of microgravity conditions aboard the KC-135A.

Continuing outreach to local students, a trip was made in the Spring of 2002 to West Morristown-Hamblin High School. There among other things, the author delivered a presentation to an honors science class as shown in Figure 4.3. This presentation included information regarding NASA's role in microgravity research and UT's participation in the RGSFOP.





Figure 4.3 – High school students listen to a presentation about the NASA RGSFOP and UT's MAMMOTH Flow entry.

For outreach on the largest scale, Knoxville, TN ABC affiliate WATE Channel 6 News aired a short segment about the MAMMOTH Flow team and our trip to Houston. Finally, at the national level, an article written by the author and Jodi Lockaby, a Daily Beacon staff writer, was published in the Spring 2002 American Institute of Aeronautics and Astronautics (AIAA) Student Journal (see Appendix E). This article brought awareness to the national student level regarding AERO and UT's participation in the RGSFOP with MAMMOTH Flow.

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## APPENDIX A KC-135 INFORMATION

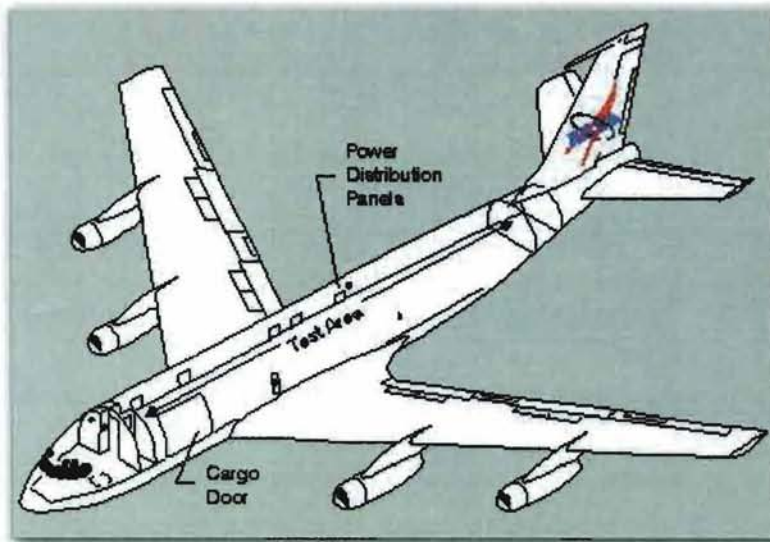
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The following information comes from the NASA KC-135A website at <http://jsc-aircraft-ops.jsc.nasa.gov/kc135/index.html>.

### About The KC-135A Aircraft:

**Aircraft:** A four-engine turbojet aircraft similar to the commercial Boeing 707

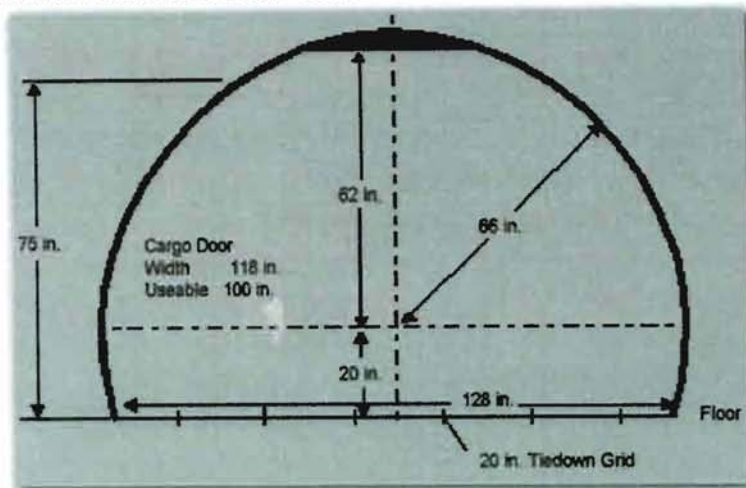
**Crew:** Pilot, copilot, flight engineer, and two reduced gravity test directors



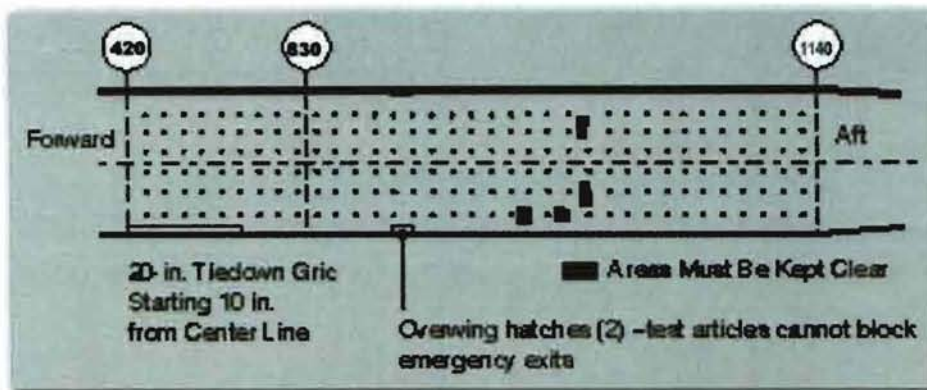
### Aircraft Description and Provisions

- Electrical power available
  - 28VDC, 80 amps
  - 110VAC, 400 Hz, single phase, 50 amps
  - 110VAC, 400 Hz, three phase, 50 amps per phase
  - 110VAC, 60 Hz, single phase, 120 amps
- Still and motion picture photography and video provided
- Most test equipment bolted to the floor using 20-inch tie down grid attachment points
- Vent/vacuum system to dump fluids overboard
- Liquid or gaseous nitrogen available
- Breathing air available

### Cabin Cross-Section View



### Floor Plan



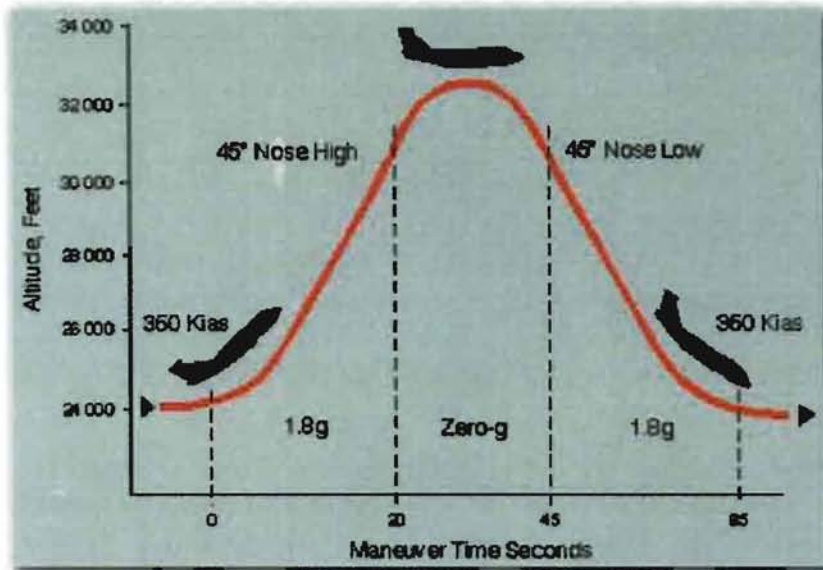
### Cargo Bay

The KC-135A cargo bay test area is approximately 60 feet long, 10 feet wide, and 7 feet high. The aircraft is equipped with electrical power, an overboard vent system, and photographic lights. Air and nitrogen sources are also available. Ground facilities include a test equipment build-up area, briefing room, fax, and telephones.

### Typical Mission

A typical mission is 2 to 3 hours long and consists of 30 to 40 parabolas. These parabolas can be flown in succession or with short breaks between maneuvers to reconfigure test equipment. The Reduced Gravity Office provides scheduling, test coordination, and in-flight direction for the test programs.

## KC-135 Flight Trajectory



The above diagram shows a typical zero-g maneuver. However, the maneuver can be modified to provide any level of g-force less than one g. Some typical g-levels used on different tests and the corresponding time for each maneuver are as follows:

- Negative-g: (-0.1 g): Approximately 15 seconds
- Zero-g: Approximately 25 seconds
- Lunar-g: (one-sixth g): Approximately 40 seconds
- Martian-g: (one-third g): Approximately 30 seconds

## **APPENDIX B    PROGRAM FLIGHT SCHEDULE**

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Time	Thursday	Friday	Sat/Sun	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
700	No Hardware Setup	Flyers/Alt Fly	On Your Own	Morning Meeting All Teams TRR Prep	Morning Meeting Group A Flight Crew Preflight at 993 Flight Suits Safety video Preflight Briefing	Morning Meeting Group A Flight Crew Preflight at 993 Flight Suits Safety video Preflight Briefing	Morning Meeting Group B Flight Crew Preflight at 993 Flight Suits Safety video Preflight Briefing	Morning Meeting Group B Flight Crew Preflight at 993 Flight Suits Safety video Preflight Briefing	M A K E  U P S
715		All Others							
730		Physiological Training							
745		Hardware Setup							
800		Continues							
815	No Hardware Setup	Meet at JSC Security Bldg 110 (Main Gate) Approx 7am	S	TRR - Begins	Takeoff & fly zero g	Takeoff & fly zero g	Takeoff & fly zero g	Takeoff & fly zero g	
830			A						
845			T						
900			U						
915			R						
930	Program Check-in & Badging		D	Return to Ellington Debrief	Return to Ellington Debrief	Return to Ellington Debrief	Return to Ellington Debrief	Return to Ellington Debrief	
945			A						
1000			Y						
1015			AND						
1030			S						
1045	Welcome to Ellington Field Safety Brf Introductions		U	Lunch on your own	Lunch on your own	Lunch on your own	Lunch on your own	Lunch on your own	
1100			N						
1115			D						
1130			A						
1145			Y						
1200	Lunch on your own	Lunch on your own		Flight Group A Uploads Briefings Suits/Forms Chamber Grp 3 Chamber Ride at NBL Finish ~5pm	Lunch on your own	Lunch on your own	Lunch on your own	Lunch on your own	
1215	Hardware Setup Begins								
1230									
1245									
1300									
1315	Newcomers Q&A at Bldg 993	Chamber Grp 1 Chamber Ride at NBL Finish ~5pm		Chamber Grp 4 Chamber Ride at NBL Finish ~6:30	Astronaut Briefing at Coast Guard Hans Schlegel	Flight Group B Uploads Motion Sick Video Safety Briefing Flight Suit Issues Mishap Forms	Tours Meet @ B110		
1330									
1345									
1400									
1415									
1430	Journalists' Briefing at Bldg 993 Ellington	Chamber Grp 2 Chamber Ride at NBL Finish ~6:30		Dinner at Joe's Crab Shack	Dinner on your own	Dinner on your own	Dinner on your own		
1445									
1500		Meet the Press Student Brf Hangar 990							
1515									
1530									
1545	Building 990/993 closes				Dinner on your own	Dinner on your own	Dinner on your own		
1600									
1615									
1630									
1645									
1700	Dinner TBD			Rock Climbing	Bowling or minigolf	Movie or ice skating			
1715									
1730									
1745									
1800									
1815	With the "Reduced Gravity Group"								
1830									
1845									
1900									
1915									
1930									
1945									
2000									

# UT students to travel to NASA

JOHN LOCKMAY  
Staff Writer

A group of students from the University of Tennessee will head to Houston on March 20 for NASA's Reduced Gravity Student Flight Opportunity Program.

This will mark the second year that UT students have participated in the program designed to "prepare America's college students for research aboard the International Space Station."

In the Reduced Gravity Student Flight Opportunity Program, NASA accepts proposals from undergraduate student teams for microgravity research experiments. If the team's proposal is accepted, the team is expected to fulfill all levels of research, design, fund raising, management and educational outreach of the project.

"It is very exciting to finally put the information that we have worked so hard to learn in the classroom to practical use," Dave Garth, a mechanical engineering major and program participant, said.

Selected teams spend a week at Ellington Field in Houston where team members have the opportunity to fly their experiments aboard NASA's KC-135. Otherwise known as the "Weightless Wonder," the KC-135 generates 30 seconds of weightless flight at a time through a parabolic flight trajectory. It generates 40 weightless parabola trajectories per flight, during which teams conduct their experiments in a weightless environment.

"Since I was three I've wanted to be an astronaut," George Hatcher, an aerospace engineering major, said. "I remember hearing rumors in grade school about a 'zero-gravity room' and never believing it. Bringing my surprise wheel found out it existed in the shape of a KC-135."

Members of the first team included Warren, Nathan Fowler, Jeremy Smith, Tim Craig, Brian Babbs and Joseph Tipton, with a proposal for MAMMOTH Flow: Making A Moving Measurement Of two-phase

Flow.

Using data obtained through microgravity experiments in 2001, the 2002 team has submitted a modification of the 2001 experiment. "MAMMOTH Flow: Phase II," Tipton, Smith, George Hatcher and Dave Garth will fly with the experiment March 28-29 while Babbs serves as ground crew.

"For the foreseeable future, this is as close as I'll come to experiencing the joys and frustration of living in space," Tipton, an aerospace engineering major and team leader of MAMMOTH Phase II, said. "I'm sure I'll get to be an astronaut for a few precious moments, and I intend to cherish that."

The goal of the MAMMOTH Flow experiment is to test different methods for increasing heat transfer for two-phase flow in microgravity conditions.

"One of the major challenges was to accurately simulate film boiling," Garth said. "One challenge that came with that was going from the theoretical idea to actually designing a part that could physically be produced."

Through participation in this program and ideas from people like Warren, the team members focused on the creation of the Aerospace Education and Research Organization at UT.

AERO has two main purposes: to provide education and research opportunities in aerospace activities to students, and to educate the local community about aerospace developments.

AERO supports the MAMMOTH project as well as other undergraduate research opportunities through NASA, like the NASA Marsport Competition.

AERO is supported by Larry Taylor, head of the Planetary Geological Institute at UT. Taylor also oversees UT's participation in the Tennessee Space Grant Consortium. The TSGC is a major supporter of AERO, helping to make participation in NASA programs possible.

For more information on AERO, MAMMOTH Flow and future student research opportunities, check out the AERO Web site at [web.aik.edu/~aeroaero](http://web.aik.edu/~aeroaero).




Special to The Daily Beacon  
University of Tennessee graduates Randy Warren and Nathan Fowler participated in NASA's Reduced Gravity Student Flight Opportunity Program last year in Houston. A group of UT students will be able to participate in the same program in Houston this month.



## APPENDIX D UNIVERSITY RESEARCH FAIR

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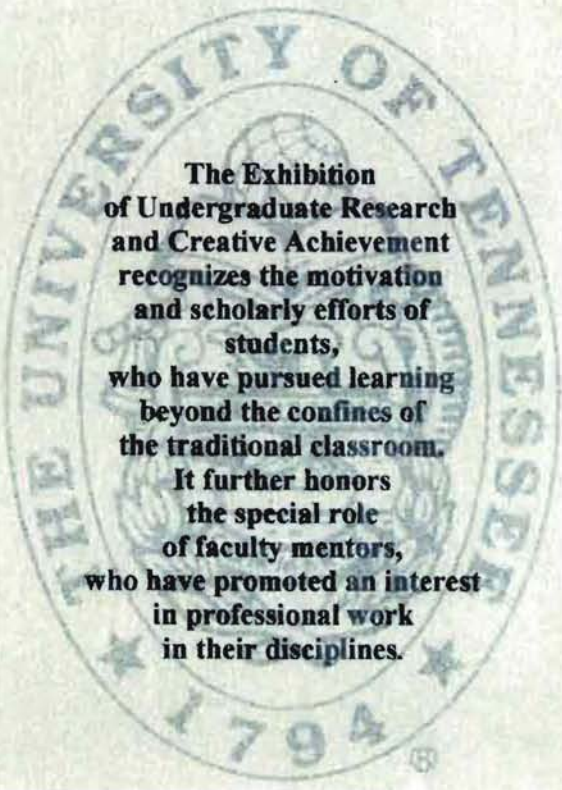


**Exhibition  
Of  
Undergraduate  
Research  
and  
Creative  
Achievement**

April 5, 2002  
9:00 a.m. - 4:00 p.m.  
University Center  
Ballroom

**The Exhibition  
of Undergraduate Research  
and Creative Achievement  
recognizes the motivation  
and scholarly efforts of  
students,  
who have pursued learning  
beyond the confines of  
the traditional classroom.  
It further honors  
the special role  
of faculty mentors,  
who have promoted an interest  
in professional work  
in their disciplines.**

**The University of  
Tennessee, Knoxville**





## APPENDIX E AIAA STUDENT JOURNAL ARTICLE

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The following information comes from the American Institute of Aeronautics and Astronautics Student Journal website at <http://www.aiaa.org/studentjournal>.

### UT Volunteers Take Flight in Houston and in the Community

By: Jodi Lockaby and Joseph Tipton

A group of students from the University of Tennessee, Knoxville recently spent their spring break in Houston to participate in NASA's Reduced Gravity Student Flight Opportunity Program.

In the RGSFOP, NASA accepts proposals from undergraduate student teams for microgravity research experiments. Selected teams are expected to fulfill all levels of research, design, fund raising, and educational outreach of the project. Teams also spend a week at Ellington Field in Houston, TX, where they have the opportunity to fly their experiments aboard NASA's KC-135 "Weightless Wonder". The KC-135 generates forty weightless parabola trajectories per flight, during which teams conduct their experiments and experience the thrill of weightlessness.

The first team from UT to participate in this program was in 2001 with a proposal entitled MAMMOTH Flow: Making A Mixing Measurement Of Two-phase Flow. Members of this team included UT mechanical and aerospace engineering students: Randy Warren, Nathan Fowler, Jeremy Smith, Tim Craig, Brian Babis, and Joseph Tipton.

Using data obtained in 2001, the 2002 team submitted a modification of the MAMMOTH Flow experiment. Joseph Tipton, George Hatcher, Jeremy Smith, and Dave Garth flew with the experiment on the KC-135 during the last week in March, while Brian Babis served as ground crew.

Students Prepare for the Weightless Wonder.



MAMMOTH Flow on Display





The goal of MAMMOTH Flow is to test different methods for increasing heat transfer for two-phase flow in microgravity conditions. The experiment aims to simulate a boiling flow by injecting a sheet of air around flowing water in a pipe. In microgravity, buoyancy is drastically reduced and, therefore, flow mixing due to natural convection is almost entirely diminished. The experiment attempts to augment this reduced flow mixing by testing two different pipe inserts. A variable diameter insert mixes the flow by inducing turbulence while a twisted tape insert mixes the flow through a swirling action. The experiment provides means to measure the enhancement of heat transfer created by flow mixing from these inserts. Greater flow mixing means greater heat transfer, which equates to greater potential for high power applications in the microgravity environment of space.

Implementing the experiment in a microgravity environment was a challenge for the students. Space limitations on board the aircraft dictated the need for a closed water loop in the system. This meant the injected air had to be removed before the water could be resent to the pump. Without gravity to separate the air and water, the MAMMOTH Flow team had to build a centrifugal accelerator to artificially create gravity.

UT owes its participation in this program to the vision and dedication of aerospace engineering graduate Randy Warren. While Randy was a junior at UT in 2000, he founded the Aerospace Education and Research Organization on campus. AERO has two main purposes: to provide education and research opportunities in aerospace activities to students, and to educate the local community about aerospace developments.

AERO supports the MAMMOTH Flow project as well as other undergraduate research opportunities. To date, student members have participated in the NASA Great Moonbuggy Race, Marsport Cryogenics and Consumables Station design competition, and a Mars Deployable Greenhouse senior design project. These projects recruit students of all science disciplines to the opportunities of aerospace research.

AERO's educational outreach focuses on UT's campus and the community at large. Campus outreach has included articles in the campus newspaper and participation in the UT Exhibition of Undergraduate Research and Creative Achievement. Outreach to the Knoxville community consists of visits to local high school science classes and local TV coverage.

Dr. Masood Parang, a mechanical engineering professor, advises the MAMMOTH Flow team. Dr. Larry Taylor, head of the Planetary Geological Institute and the Tennessee Space Grant Consortium at UT, is the AERO faculty advisor. The TSGC is a huge supporter of AERO, helping to make participation in NASA programs possible. For more information on AERO and MAMMOTH Flow, please check out the AERO [Web site](#).

UT Students in front of the Weightless Wonder.

